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a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		19a. NAME OF RESPONSIBLE PERSON Eric Paulson
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Epitrochoid Power-Law Nozzle Rapid Prototype Build/Test Project

Mr. Eric J. Paulson-Vehicle Analyst
Rocket Propulsion Division
Combustion devices Branch
Systems Analysis Group



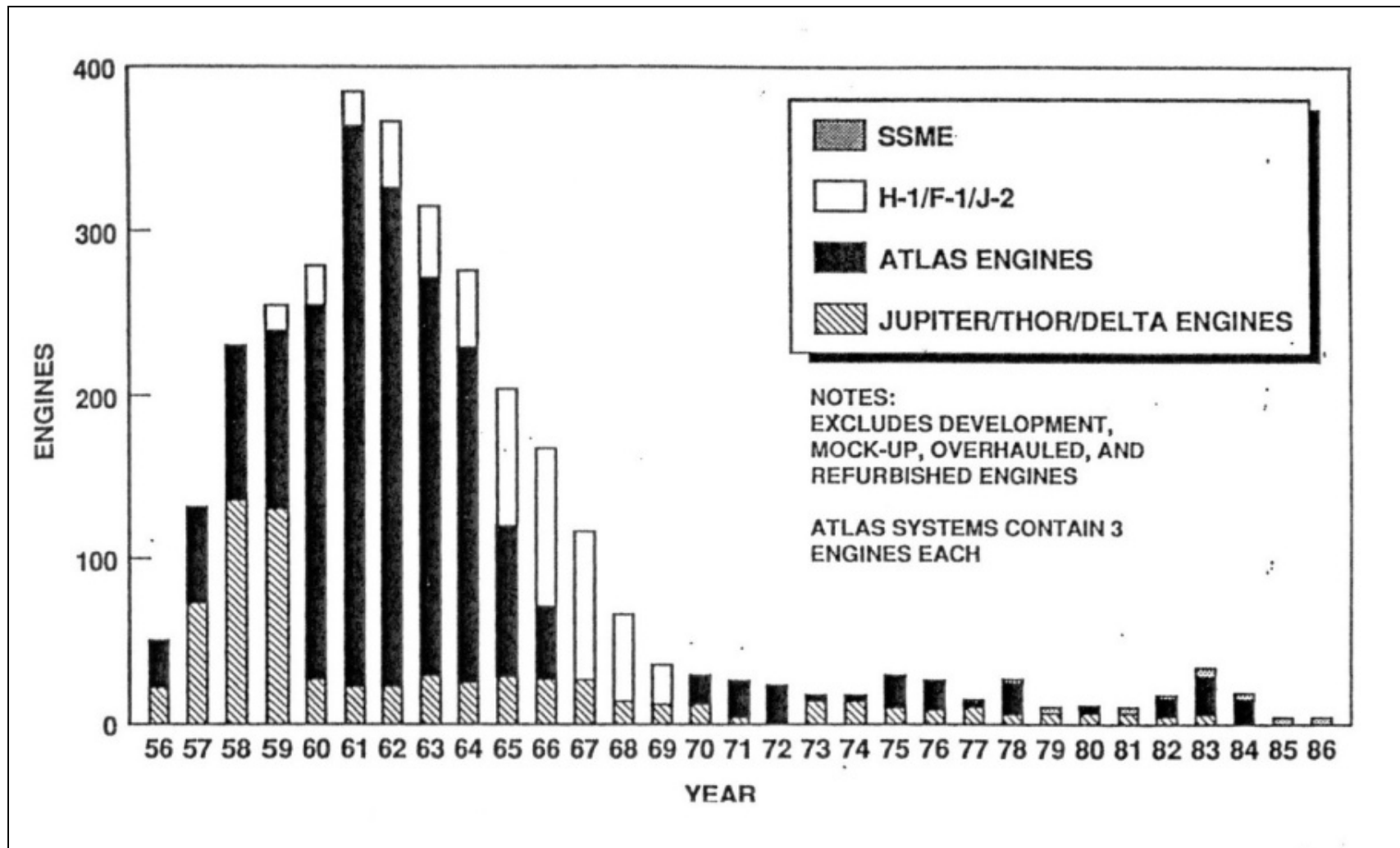
Epitrochoid Power-Law Nozzle Build/Test Overview



- Who:
 - **PM: Eric Paulson** RQRC Systems Analysis Group
 - Partners: Dr. Shelley, Lancaster University Center
- What: **6-month** Rapid Prototype Build/Test **N₂ cold flow prototype** of Epitrochoid Power-law Nozzle (EPN)
- Where: Lancaster University Center (LUC)
- Why:
 - Demo initial proof of concept for new 3D multiple plume nozzle
 - Demo new cold flow nozzle manufacture/test approach
- Cost: **To Be Determined (TBD)**



Economics of Decreasing Annual Rocket Engine Production



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Epitrochoid Power-Law Nozzle Build/Test

Build on SpaceX Multiengine Approach



Engines: Merlin 1D on Falcon 9 v1.1 (Photo SpaceX)

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Epitrochoid Power-Law Nozzle Build/Test

Under-to-over expansion of Multiple Plumes



- **Falcon 9 launch video here**



Epitrochoid Power-Law Nozzle Build/Test

A Type of Radially Lobed Nozzle



Lobed Nozzle Extension for Better Gas Dynamic Incorporation of Modular Thrust Cells Exhaust

- Implementation Requires a Parametric Design of Lobed Shape
- Epitrochoid Planar Curve Fits the Bill

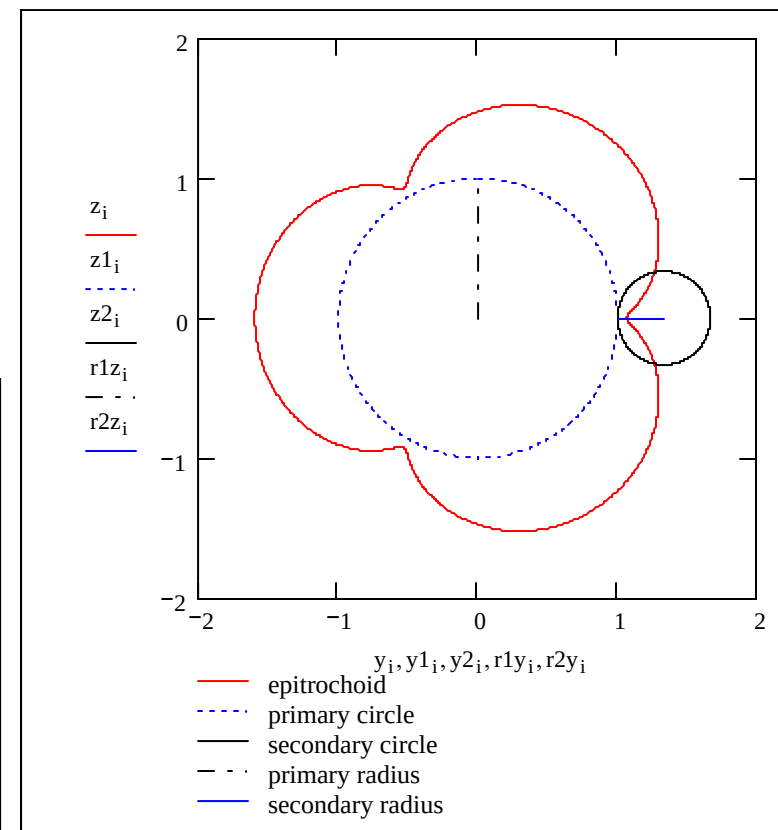
Parameterized by $R1$, $R2$, k , and d

$R1$: primary circle radius

$R2$: secondary circle radius

k : ratio of $R1/R2$

d : normalized generating parameter



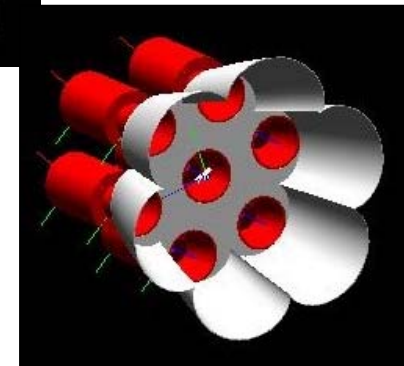
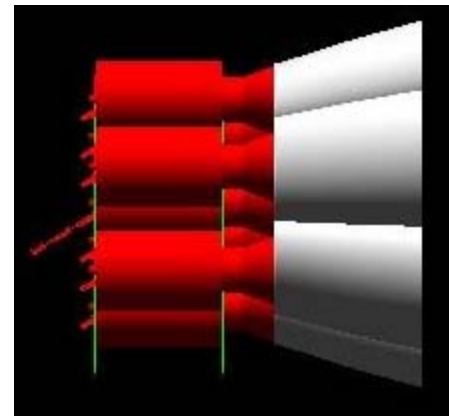
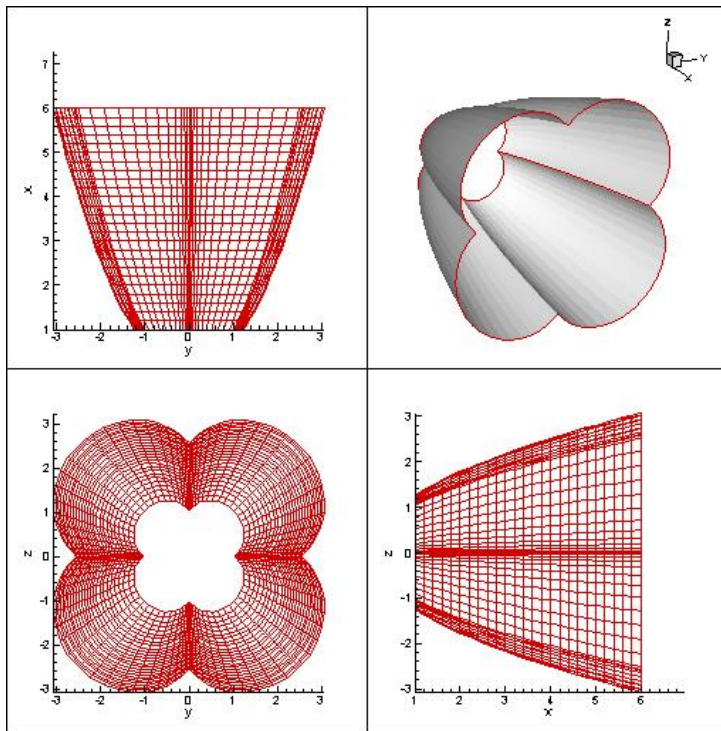


Epitrochoid Power-Law Nozzle Build/Test

Nozzle Extension Surface Definition



A power-law relationship for R1 primary circle radius as function of x defines a semi-infinite surface from $x=0$ plane. Adding $x_{\min}$ & $x_{\max}$ bounds creates a diverging radially lobed nozzle extension shape.



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Typical Nozzle Test Article Costs



- Multiple nozzle cold-flow testing using traditional manufacture would be prohibitive
 - Typically 1-3 test articles tested over 8 week test period in cold-flow facility
 - Currently: \$30-100k manufacturing cost per metallic test nozzle depending on complexity
 - \$30k for mechanical design of test article
- NASA-MSFC Rapid Prototyping Demo costs: \$3-5K for in-house manufacture & process development, per nozzle

Manufacturing cost reduction of 90-95% per nozzle test article

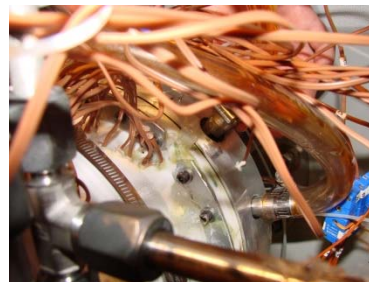


NASA-MSFC Lessons

New Material Requires New Design Approach



- **Weaker than metal**
 - distribute flange loads
- **Thermal insulator instead of conductor**
 - account for thermal gradients
- **Avoid multipart designs with lots seals:**
 - build in the passages
 - “Cartridge” test article and housing



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Takeaway Questions

Objectives



- **Objectives**
 - **Develop extremely cheap and fast method to build experimental test nozzles**
 - **Develop extremely cheap and fast test rig to bench-level sea-level cold flow test**
 - **Develop cheap/fast method to build lobed Epitrochoid Power-law (EP) nozzle extension**
 - **Demo proof-of-concept cold flow testing of the EP nozzle**



Takeaway Questions

Why is This Innovative



- Some related work occurring in industry: metallic additive mfg demoed/used for small thrust cells, propellant injectors and valve housings
- Cold flow nozzles are being built same way as they were in 1960.
 - EP nozzle: a new way to utilize features of high performance engines advances and the economies of scale of the multi-engine approach of SpaceX Falcon 9
 - Rapid Prototype cold flow testing:
 - Enable order-of-magnitude cost reduction for build
 - Enable extremely rapid, affordable design exploration for 3D classes of nozzles



Takeaway Questions

What is Success?



- **Lots of off ramps to declare success**
 - **Feasible new quick/cheap cold flow test design approach (criteria=better than current approach with usable wall pressure data)**
 - **Feasible to build axisymmetric cold flow nozzle test articles using plastic-based inexpensive rapid additive manufacturing**
 - **Feasible to rapid prototype lobed nozzle extension**
 - **Feasible lobed nozzle extension**
- **Criteria=demo proof-of-concept for stable full-flowing lobed nozzle at sea level**

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Why Choose to Work This Project?



- **Fame, glory, and the accolades of your peers...**
- **Opportunity to legitimately call yourself a rocket engineer**
- **Chance to work on something cutting edge**
 - **No other teams in US working on low cost cold-flow test nozzle designs currently**
 - **The lobed epitrochoid power-law nozzle concept is new and original: you're looking at the inventor**
- **Opportunity to publish/present the initial results for what may continue into a bigger program**